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Low Temperature Low-Earth-Orbit Testing of Mars Surveyor Program Lander Lithium-Ion Battery

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November 2005

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Abstract

A flight-qualified, lithium-ion (Li-ion) battery fabricated for the Mars Surveyor Program 2001 lander is undergoing life-testing at low temperature under a low-Earth-orbit (LEO) profile to assess its capability to provide long term energy storage for aerospace missions. Li-ion batteries are excellent candidates to provide power and energy storage for satellites in LEO due to their high specific energy, high energy density, and excellent low temperature performance. Although Li-ion batteries are increasingly being used for aerospace missions in geosynchronous orbit, some challenges still remain before they can be deemed a suitable replacement for their secondary alkaline battery counterparts in long cycle life LEO applications. Life cycle testing of this battery is being conducted in the laboratory to characterize battery-level performance and to examine the dynamics of individual cells within the stack under aerospace conditions. Data generated in this work is critical to establish confidence in the technology for its widespread use in manned and unmanned missions. This paper discusses the performance of the 28 volt, 25 ampere-hour battery through 9000 LEO cycles, which corresponds to over 18 months on LEO orbit. Testing is conducted at 0 °C and 40 percent depth-of-discharge. Individual cell behaviors and their effect on the performance of the battery are described. Capacity, impedance, energy efficiency, end-of-discharge voltages, and cell voltage dispersions are reported. Relationships between cell temperatures, cell impedance, and their relative position in the battery stack are discussed.

I. Introduction

Testing of lithium-ion (Li-ion) cells and batteries is being conducted by the National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC) and other partner organizations to assess their capability to perform under a variety of conditions and temperatures in simulated low-Earth-orbit (LEO) regimes.

Currently, nickel-hydrogen (Ni-H_2) and nickel-cadmium (Ni-Cd) batteries provide energy storage for the majority of satellites in LEO. Li-based battery technology initially broke ground in its utilization in the US space program due to its ability to enable missions operating in low temperature environments, such as Mars. In addition to its low temperature capability, Li-ion offers improvements in mass, volume, efficiency, and operating temperature range over secondary (rechargeable) alkaline battery chemistries.

At present, Li-ion liquid electrolyte batteries provide 2.5 times the specific energy and 4.5 times the energy density of state-of-the-art Ni-H_2 batteries when operating at 100 percent depth-of-discharge (DOD), and advancements continue to be made. Li-ion batteries have a high nominal cell level operating voltage compared to Ni-H_2 batteries (3.6 volts (V) versus 1.2 V), so fewer Li-ion cells are required to meet the bus voltage. Hence, fewer intercell connections are required in the battery assembly, which provides the system with greater simplicity and reliability.

Long cycle life is an essential performance metric for batteries in LEO. Since most satellites in LEO operate for five years or more while delivering electrical energy during approximately 16 cycles per day, the energy storage system must be capable of providing upwards of 30,000 cycles. Since a Li-ion battery that has the equivalent mass and voltage of a Ni-H_2 battery can operate at a much lower DOD, the cycle life of the battery could be extended due to the lower DOD requirement, which is a more benign operating condition. If Li-ion technology is able to meet the cycle life requirements of a mission while operating at a higher DOD, the resulting mass and volume savings in the energy storage system could contribute to increased payload capability onboard the spacecraft.

Some practical issues that contribute to the increased use of Li-ion batteries in space are that Li-ion batteries are less expensive than Ni-H_2 batteries and that Ni-H_2 technology is in danger of becoming obsolete (ref. 1). Aerospace Li-ion cell and battery research and development efforts can benefit from ongoing advances in the thriving commercial Li-ion battery market, as well as from common NASA/military drivers for targeted improvements in the technology. Joint development efforts and the spinning-in of commercial technology for aerospace applications allow for certain development costs to be shared or reduced (ref. 2).

Prior to routine use, real-time life testing of Li-ion batteries is required to assess multicell battery-level performance, establish cycle life, and otherwise validate the chemistry for its flight readiness for LEO and other types of aerospace missions. Results reported on in this paper will contribute valuable data to the ongoing assessment of the life performance of Li-ion aerospace battery technology and the low temperature operation of Li-ion batteries, and will help to establish confidence in the technology for its widespread use in manned and unmanned missions.

II. Background

The 28 V, 25 ampere-hour (Ah) battery was designed and built for the 2001 Mars Surveyor Program Lander, and was therefore designed to operate at the low temperatures that it would endure on the surface of Mars*. The battery contains 8 prismatic Li-ion cells connected in series with no charge balancing electronics. The cells contain a liquid organic electrolyte, a mesocarbon microbeads (MCMB) anode and a $LiNiCoO_2$ cathode. Li-ion batteries of this vintage typically deliver drastically reduced capacity at low temperatures. In addition, rate capability can also suffer. Due to the low temperature requirements of the original mission, a special electrolyte formulation was used in the cells to enhance conductivity, improve the redox stability at the electrodes, and provide better rate capability (ref. 7). Manufacturer characteristics of the battery are shown in table 1.

TABLE 1.—MANUFACTURER SPECIFICATIONS OF THE MARS SURVEYOR PROGRAM LANDER BATTERY

Cell/Battery Manufacturer	Yardney Technical Products, Inc.
Nameplate Capacity	25 Ah
Rated Capacity	30 Ah at C/5 at 20 °C; 24 Ah at C/5 at –20 °C
Nominal Voltage	28.8 V
Operating temperature	–20 to 40 °C
Cell type	Prismatic
Number of Cells	8
Anode	Mesocarbon microbeads (MCMB)
Cathode	$LiNiCoO_2$
Electrolyte	1.0 M $LiPF_6$ EC+DMC+DEC (1:1:1)
Design Mission	Storage: Up to two years, one year of which during cruise to Mars at 0 to 30 °C Entry, descent and landing (EDL) on Mars: Several 2C pulses, 100 milliseconds in duration at 0 °C Operation on Mars: Minimum of 90 cycles, typical discharge of C/5 at a maximum of 50 percent DOD at –20 to 40 °C
Special Operating Considerations	Can operate under any orientation and in zero-gravity

Source: Yardney Technical Products, JPL (ref. 4)

The 2001 Mars Surveyor Program was the first major NASA mission that baselined Li-ion battery technology. In addition to the battery being reported on in this paper, four other flight batteries of the same design were built for the program. Following the cancellation of the mission due to programmatic issues, a coordinated plan was developed among several organizations to evaluate the performance of all five batteries under a variety of conditions. In addition to NASA GRC, other participating organizations include the NASA Jet Propulsion Laboratory (JPL), the Naval Research Laboratory (NRL), and the Air Force Research Laboratory (AFRL). The batteries have undergone testing in various LEO, geosynchronous orbit (GEO), and planetary mission profile regimes. NASA GRC's role in the test program is to perform low temperature LEO testing at specific orbital parameters. Reports on this work and other testing efforts with cells of the same design from which these batteries were built are available in the literature (refs. 3 to 6). As a result of these and other related test programs, this battery design has been baselined for the 2007 Phoenix Mars Lander scout mission.

III. Storage

The battery was stored at open circuit at 15 degrees Celsius (°C) and 50 percent state-of-charge (SOC) (roughly 3.6 V/cell) for almost two years prior to beginning characterization in preparation for LEO testing (referred to from here on as pre-LEO characterization). The cells displayed extremely low self-discharge while in storage (less than 0.5 percent per month). The OCVs of the cells after storage is shown in the second column of table 2. Due to the

* For actual operation on Mars, the battery would have been housed in a warm electronics box passively heated by a radioisotope thermoelectric generator (RTG) to prevent it from being exposed to extremely cold temperatures. The average recorded temperature on Mars is –63 °C.

excellent cell and battery voltages after storage and the fact that the battery delivered greater than nameplate capacity during its pre-LEO characterization, no wake-up procedures were required after the two year storage period.

TABLE 2.—CELL OCVS BEFORE CYCLING

Cell	OCV after Storage (V)	Pre-LEO OCV (after Equipment Malfunction) (V)
1	3.55	3.50
2	3.55	3.47
3	3.34	1.55
4	3.54	3.35
5	3.48	3.25
6	3.46	3.34
7	3.42	3.37
8	3.53	3.51

IV. Experimental

Testing involves pre-LEO characterization, followed by life-testing under LEO conditions at 40 percent DOD and 0 °C. Periodic characterization tests are run at 1000 cycle intervals, and cell balancing is performed as required. Parameters for each of these test procedures are summarized in table 3.

TABLE 3.—BATTERY TEST CONDITIONS AND PROCEDURES

<table>
<tr><th colspan="2">Test Conditions</th><th>Test Procedure</th></tr>
<tr><td colspan="2">Pre-LEO</td><td>• Measure OCV.
• Discharge at a constant current of C/5 (5 A) to 24 V or until any cell reaches 3 V in order to measure residual capacity.
• Perform baseline capacity measurements for several conditions and temperatures. If test temperature will change, soak battery for at least 24 hours at new test temperature before test.
1. At 20 °C, charge at a constant current of C/5 (5 A) to 32 V or until any cell reaches 4.05 V; hold voltage constant and continue to charge until current tapers to C/50 (0.5 A); discharge at C/5 (5 A) to 24.0 V or until any cell reaches 2.5 V.
2. At 23 °C, charge at a constant current of C/2 (12.5 A) to 32.8 V or until any cell reaches 4.05 V; hold voltage constant and continue to charge until current tapers to C/125 (0.2 A); discharge at C/2 (12.5 A) to 24.0 V or until any cell reaches 3 V.
3. Repeat step 1 at 0 °C.
4. 100 percent DOD Capacity Test at 0 °C (as given below in this table)</td></tr>
<tr><td colspan="2">LEO</td><td>• Charge at a constant current of C/2 (12.5 A) to 32 V or until any cell reaches 4.05 V.
• Hold voltage constant and continue to charge for the remainder of the 55 minute charge period.
• Discharge at 0.7C (17.14 A) for 35 minutes (to 40 percent DOD).
• Failure is defined when EODV is 24 or 2.5 V on any cell.</td></tr>
<tr><td rowspan="2">1000 Cycle Characterization</td><td>100% DOD Capacity Test</td><td>• Continue LEO discharge at 0.7C (17.14 A) to 24.0 V or until any cell reaches 2.5 V.
• Charge at a constant current of C/2 (12.5 A) to 32 V or until any cell reaches 4.05 V.
• Hold voltage constant and continue to charge until current tapers to C/50 (0.5 A).
• Discharge at 0.7C (17.14 A) to 24.0 V or until any cell reaches 2.5 V.</td></tr>
<tr><td>DC Impedance</td><td>1. Charge at a constant current of C/5 (5 A) to 32.4 V.
2. Rest at OCV for 2 hours.
3. Discharge at a constant current of 1C (25 A) for 10 seconds.
4. Rest at OCV for 2 hours.
5. Discharge at a constant current of C/10 (2.5 A) for 2 hours (remove 5 Ah).
6. Repeat steps 2 to 5 four times (at each of 80, 60, 40 and 20 percent SOCs).</td></tr>
<tr><td colspan="2">Cell Balancing</td><td>1. Discharge at a constant current of C/5 (5 A) to 24 V or until any cell reaches 3 V.
2. Discharge at a constant current of C/50 (0.5 A) until any cell reaches 2.75 V. Allow voltages to recover at open circuit.
3. Individually drain discharge remaining 7 cells to 2.75 V using a 1 ohm (Ω) resistor. Allow voltages to recover at open circuit.
4. Charge at a constant current of C/5 (5 A) to 32.8 V or until any cell reaches 4.1 V.
5. Hold voltage constant and continue to charge until current tapers to C/125 (0.2 A).
6. Repeat steps 1 to 3, then perform a drain discharge of individual cells to 2.75 V using 1.5 Ω resistor.
7. Repeat 100 percent DOD Capacity test.</td></tr>
</table>

Pre-LEO characterization was performed after the battery was removed from storage. LEO testing was initiated after pre-LEO characterization was completed.

Cell balancing is performed during a regularly scheduled 1000 cycle characterization if the cell voltage dispersion exceeds 100 millivolts (mV) on charge or 80 mV on discharge. The cell voltage dispersion on charge exceeded 100 mV at cycle 6510, so cell balancing was performed at the 7000 cycle characterization interval.

Since cell balancing was performed after 7000 LEO cycles, there are noticeable discontinuities in the data before and after cell balancing. These two data series will be addressed separately throughout this paper.

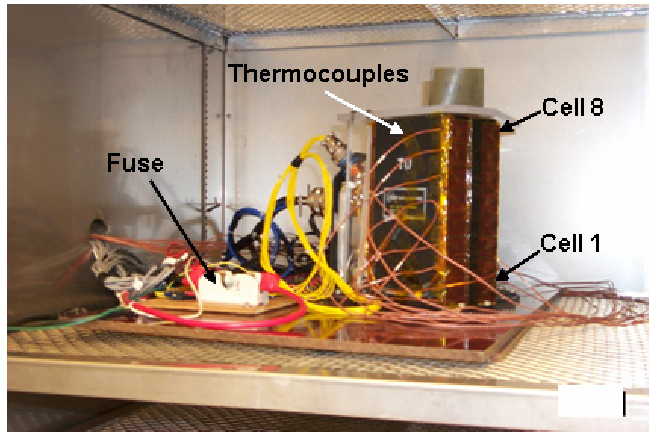


Figure 1.—Mars Surveyor Program Lander Battery test set-up.

Testing is performed using an Arbin Instruments Model BT2000 battery cycler. Current, battery voltage, cell voltages, and cell temperatures (outside case) are continually monitored. The battery is tested under an inert atmosphere within an environmental chamber that is held at a constant temperature of 0 °C during LEO testing and periodic characterization. During pre-LEO characterization, the chamber was set to the temperature required for each test and the battery was soaked at that temperature for at least 24 hours before testing. Cell balancing is conducted at room temperature because portions of this procedure must be done manually. After cell balancing, the battery is soaked at 0 °C for at least 24 hours before characterization and testing continues. Figure 1 shows a picture of the battery in the test chamber. Cell 1 is located at the bottom of the stack. Cell 8 is located at the top of the stack. Thermocouples are located on the side of each cell near the top of the case (cells are oriented sideways in the battery to form the stack). A 30 ampere (A) fuse is connected in-line with the positive current cable that connects the battery cycler to the battery to prevent accidental over currents.

V. Pre-LEO Characterization

A pre-LEO characterization procedure was performed when the battery was removed from storage. A C/5 (5 A) discharge was initiated to measure the residual capacity in the battery. During this discharge, an equipment malfunction caused Cell 3 to over discharge to 1.55 V, well below the 2.5 V vendor-recommended safe operating limit of the cell. The test was terminated after 30 seconds, after which the open circuit voltage (OCV) of Cell 3 was monitored, but it did not recover on its own. The voltage on the cell was recovered by charging it at 1 A constant current while it was electrically disconnected from the seven other cells in the battery. Cell balancing was then required to restore its voltage to the same nominal voltage of the other cells. After the cells were balanced, it was observed that their OCVs were within 20 mV of each other after a one hour rest period. Pre-LEO characterization procedures were then resumed. There has been no indication of any reduced performance on Cell 3 during subsequent cycling. Table 2 shows the OCVs of each cell after storage, compared to their voltages after the equipment malfunction.

Before commencing LEO testing, the battery underwent several characterization tests. To determine the effects of low temperature operation on the capacity of the battery, 100 percent DOD baseline capacity tests were performed at 20 and 0 °C using identical test conditions. At each temperature, a constant current charge was performed at C/5 (5 A) until the battery voltage reached 32 V or until any of the cell voltages reached 4.05 V. The battery voltage was then held constant and charging continued until the current tapered to C/50 (0.5 A). The battery was then discharged at C/5 (5 A) until its voltage reached 24.0 V or any of the cell voltages reached 2.5 V. These and other baseline capacity test conditions are described in table 3 under Pre-LEO characterization. The results of the C/5, 20 °C and 0 °C are shown in figure 2. 30.6 Ah were delivered at 20 °C, versus 27.4 Ah at 0 °C. The battery was charged at the discharge temperature for each case. Because the battery was charged at the colder temperature for the 0 °C case, there was less capacity available in the battery prior to its discharge at that temperature than for the 20 °C case.

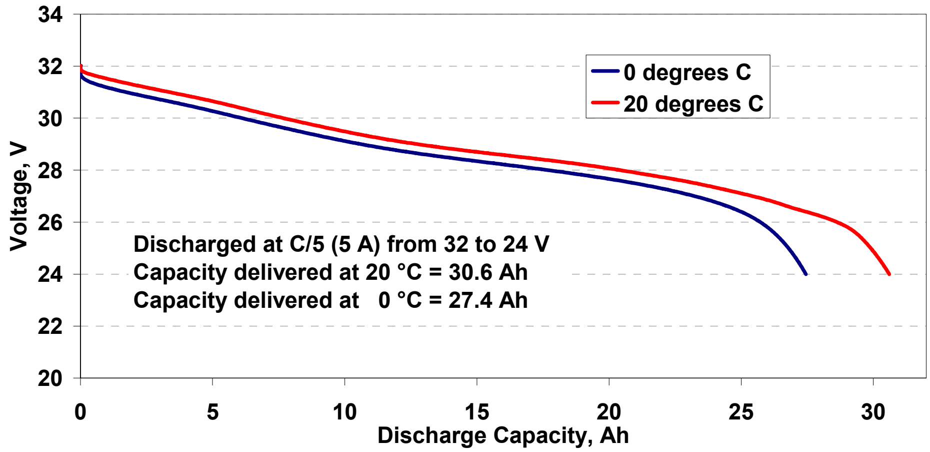


Figure 2.—Pre-LEO capacity at 0 and 20 °C.

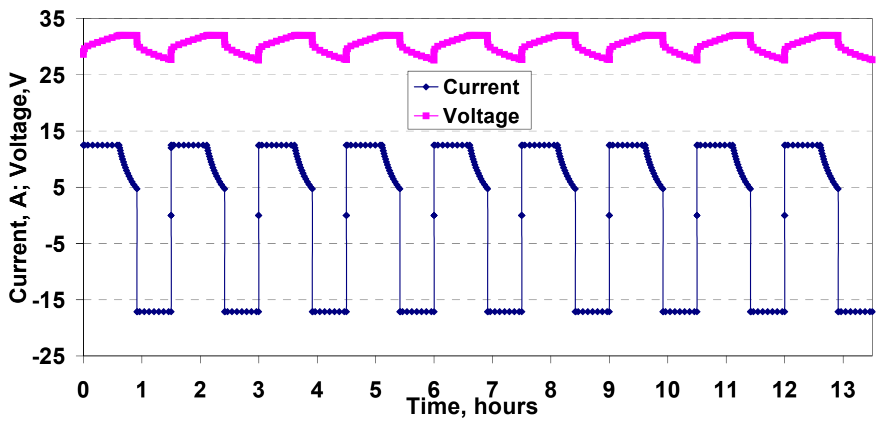


Figure 3.—LEO cycling on the Mars Surveyor Program Battery.

VI. LEO Cycling

A LEO orbit period varies slightly depending upon the orbit altitude, from 86.48 to 105.12 minutes at altitudes of 100 and 1000 km, respectively (ref. 8). A nominal 90 minute orbit period was selected for this testing. During 55 minutes of the orbit, the spacecraft is exposed to sunlight. Solar panels provide primary power to the spacecraft and provide energy to charge the batteries.

For this testing, the battery is charged using a constant-current/constant-voltage profile. The battery is charged at C/2 (12.5 A) to 32 V or until the first cell reaches 4.05 V. Next, the battery voltage is held constant while the current is allowed to taper for the remainder of the 55 minute charge period. This two-step charge regime allows for additional capacity to be added to the battery once it has achieved its upper voltage cut-off limit, without increasing its voltage beyond the acceptable limits.

For the remaining 35 minutes of the orbit, the sun is eclipsed by the Earth (with respect to the satellite), which results in the satellite being in shadow. During this time, the battery discharges to provide primary power to the spacecraft. A discharge rate of 17.14 A (about 0.7C) was required to discharge 40 percent of the capacity of the battery (10 Ah) during the 35 minute eclipse portion of the orbit. The 40 percent DOD was chosen for this testing in order to test the outer envelope of possible DODs for Li-ion batteries for LEO applications. The test will continue until the battery fails. Battery failure is defined as the point when the battery end-of-discharge-voltage (EODV) reaches 24 V or when any cell reaches 2.5 V during a LEO discharge. To date, the battery has accumulated over 9000 cycles, equivalent to more than 18 months in LEO. Figure 3 shows representative current and battery voltage over several cycles near the beginning of the LEO cycling.

Figure 4 shows the individual cell voltages versus time during LEO cycling near the beginning of life, just before cell balancing, and just after cell balancing. At the beginning of life, the cell voltages are operating tightly together and average 3.5 V at the end of discharge. Before cell balancing, at almost 7000 cycles, the cell voltages are separating, with Cells 6 and 7 never achieving full charge before the battery reaches its cut-off voltage. The EODV of the cells averages 3.42 V at 6997 cycles and 3.44 V at 7100 cycles. The increase in the average EODV of the cells is due to cell balancing.

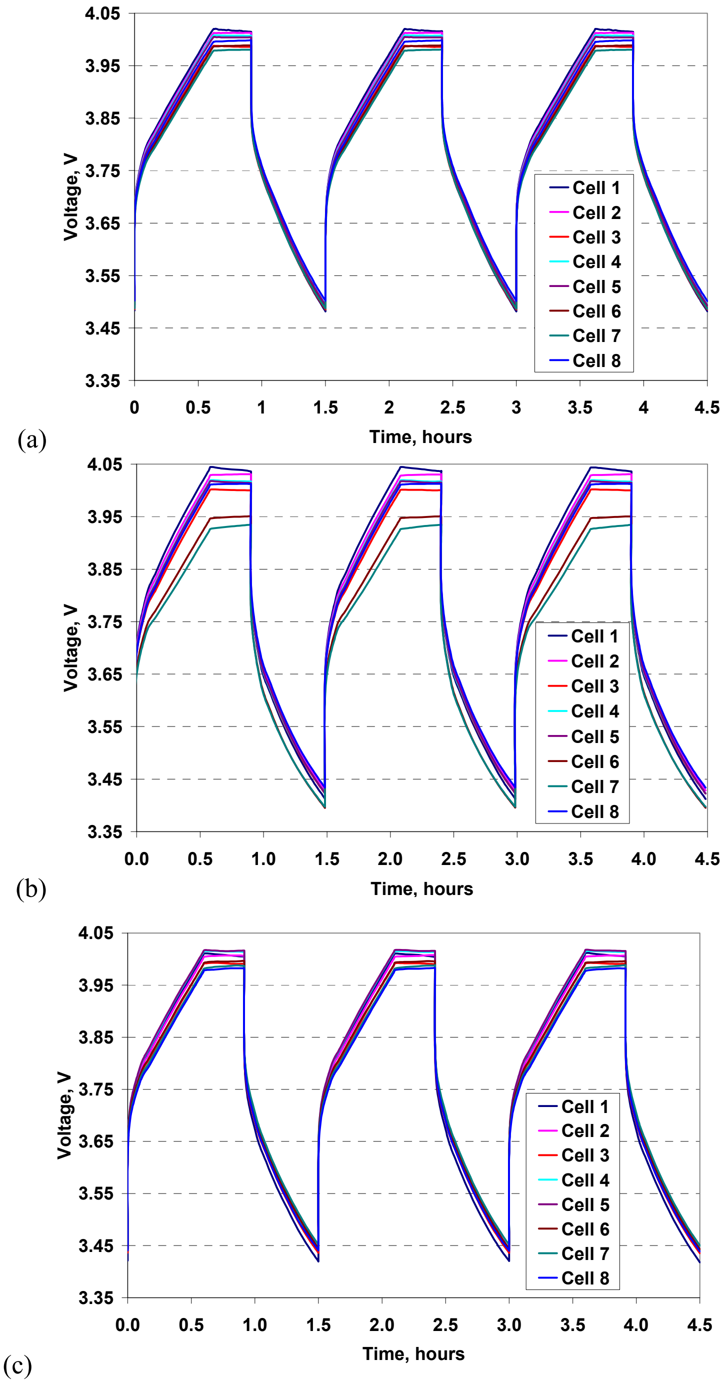


Figure 4.—Cell Voltages during LEO: (a) Cycles 10–13; (b) Cycles 6995–6997; and (c) Cycles 7100–7102.

VII. Periodic Characterization

Periodic characterization tests are conducted to assess the overall state of health of the battery. Capacity and impedance checks are performed every 1000 cycles.

A. 100% DOD Capacity Test

To measure battery capacity, following 1000 LEO cycles, the battery is allowed to continue discharging at its LEO rate until the battery voltage reaches 24 V or any cell voltage reaches 2.5 V. This process allows us to determine the capacity remaining in the battery. Full capacity is then measured by conducting a 100 percent DOD capacity test. The battery is charged at a constant current of C/2 (12.5 A) to 32 V or until any cell reaches 4.05 V. The battery voltage is then held constant until the current tapers to C/50 (0.5 A). The battery is then discharged at the LEO rate to 24.0 V or until any cell reaches 2.5 V.

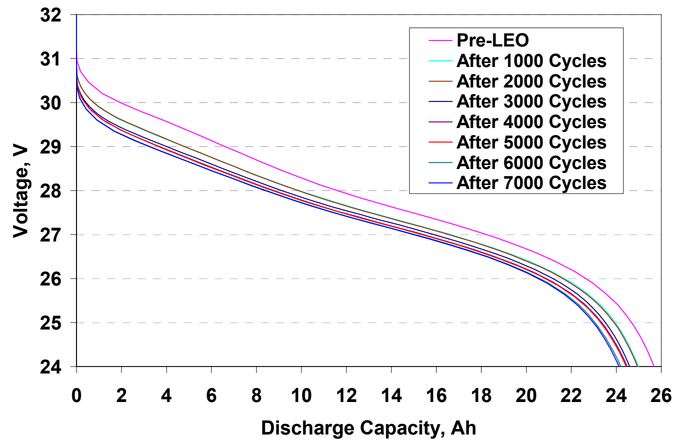
The full capacity that the battery can deliver decreases as the battery cycles. Figure 5 shows the 100 percent DOD capacity at each 1000 cycle interval. Full capacity delivered decreased from the 25.7 Ahr delivered during the initial capacity test to 24.1 Ahr at 7000 cycles. Because the cell voltage dispersion was reduced significantly after the cells were balanced, the capacity delivered immediately after the cells were balanced increased by 0.5 Ahr to 24.6 Ah, equivalent to the capacity delivered at 3000 cycles. Capacities measured at all intervals are given in table 4. Further details on cell balancing are discussed later in the section on Cell Balancing.

B. Current-Interrupt Impedance Test

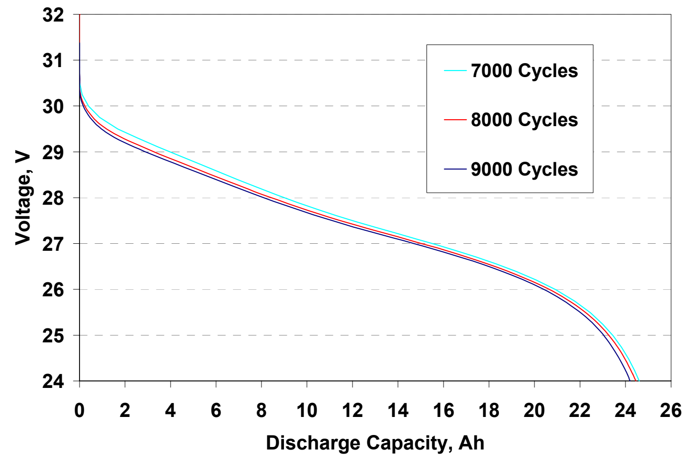
Current-interrupt impedance tests are performed in which the DC impedance is measured at different SOCs. The battery impedance at each SOC increases as the battery cycles, indicating that electrochemical aging is occurring in the battery. Figure 6 shows the DC battery impedance at 1000 cycle intervals to 6000 cycles.

VIII. Cell Balancing

Cell balancing results in individual cell voltages being brought tightly together so that they operate at similar SOCs. This procedure provides for better overall uniform health of the battery system. As discussed previously, before initializing this life test, the eight cells were uniformly balanced. As cycling continues, the cells tend to drift apart. If allowed to continue cycling in this manner, an individual cell may



(a)



(b)

Figure 5.—Capacity delivered at 1000 cycle intervals after a full charge and a discharge to 100 percent DOD: (a) before cell balancing; and (b) after cell balancing.

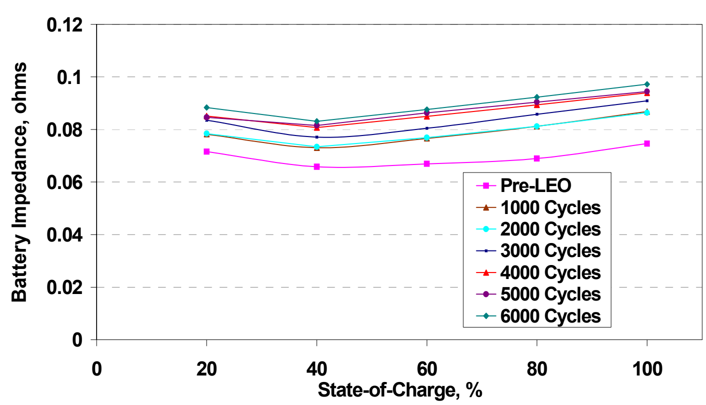


Figure 6.—Battery impedance at 1000 cycle intervals.

reach its cut-off voltage before adequate capacity is delivered to the load, causing battery failure. A cell balancing procedure can be performed to bring the cell voltages closer together so the battery can deliver the required capacity over a longer period of time.

Although the battery manufacturer specified that cell balancing should occur when cell voltage dispersion is 250 mV, we chose more conservative values of 80 mV on discharge or 100 mV on charge for this testing. Under these conditions, cell balancing was required after 7000 cycles, when the cell voltage separation on charge exceeded 100 mV. As shown in figure 7, once the cells were balanced, the cell voltage dispersion on both charge and discharge was reduced from 102 to 39 mV and from 39 to 32 mV, respectively.

In actual orbit conditions, the cells should ideally be balanced as seldom as possible, since payload operations may be impacted during battery maintenance. However, depending upon the mission, performing this type of maintenance on orbit may not be an option. Other options to maintain cell balance are to allow the battery to charge to a higher EOCV at predetermined conditions, i.e., when the battery EODV reaches a certain value, or to integrate charge balancing electronics with the battery that would continually balance the cells with each cycle (refs. 9 and 10). This particular battery was not specifically designed to operate under LEO conditions, so it was not optimized to deliver thousands of cycles without the need for cell balancing.

Cell balancing was performed after 14 months of cycling. For a 5 year mission, assuming a linear degradation, this indicates that such maintenance would be required a minimum of 3 to 4 times over the life of the mission. The time between balancing could be extended, depending upon whether or not more cell voltage dispersion would be tolerated. If the end-of-charge voltages of the cells were allowed to separate more, this type of maintenance could be required fewer times during the life of a 5 year LEO mission. This would be contingent upon whether the battery and each of the cells are able to continue to perform above their recommended cut-off voltages and whether the battery is still able to deliver the required capacity over as many cycles.

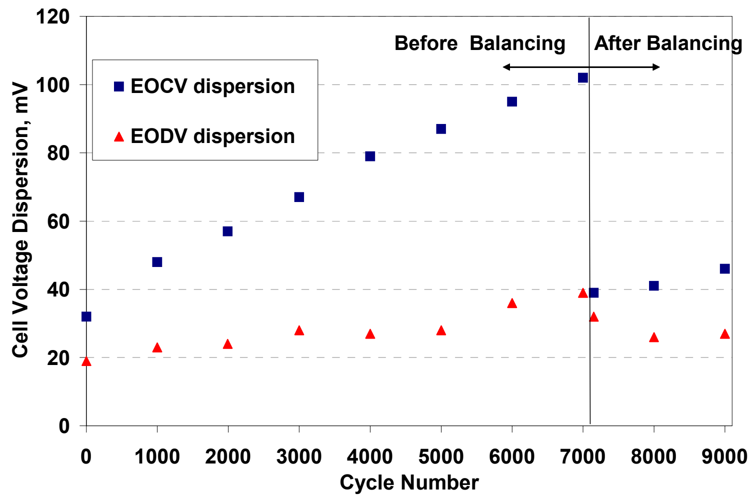


Figure 7.—Cell voltage dispersion on charge and discharge.

IX. Battery Performance Summary

A. Efficiency

Li-ion battery chemistries typically display excellent efficiencies. For this battery, coulombic efficiency is consistently 100 percent throughout LEO cycling. The test battery demonstrates energy efficiency between 90 and 93 percent during LEO cycling.

Figure 8 shows energy efficiency versus cycle number during LEO cycling. The energy efficiency increase between cycles 4500 and cycles 5300, is attributed to equipment calibration errors. (Stray measurement values are the result of test interruptions for periodic characterization or utility outages.)

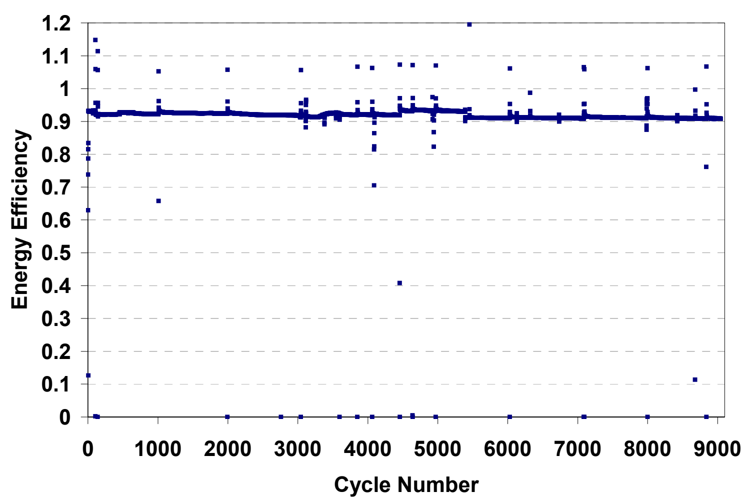


Figure 8.—Energy efficiency during LEO cycling.

B. EODV Performance

During cycling, the battery loses capacity and its impedance increases, resulting in a lower EODV with increasing number of cycles, as shown in figure 9. A linear trend projection of the performance over the first 7000 cycles would predict a battery EODV of approximately 26.3 V at 30,000 cycles (if the cells had not been balanced). This is well above the 24 V minimum battery voltage level. The electrochemical processes that contribute to battery aging have not been accurately modeled in this simple projection, so at some point during the battery cycle life, there may be some discontinuities in the EODV curve that will not follow the current trend. (Stray measurement values are the result of test interruptions for periodic characterization or utility outages).

Some of the capacity loss appears to be reversible, and can be recovered through reconditioning the battery. As seen in figure 10, periodic characterization procedures appear to have a "reconditioning effect" on cell balancing, as evidenced by the fact that the cell voltage dispersion on charge and discharge is reduced after capacity and impedance testing have been performed. This reconditioning leads to a higher battery EODV during LEO cycling. After cycle 7000, the EODV was increased and the cell voltage dispersion was decreased due to a combination of this reconditioning and the cell balancing procedure.

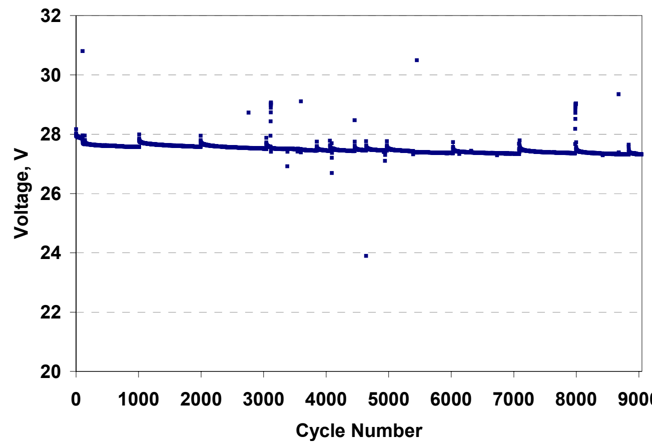
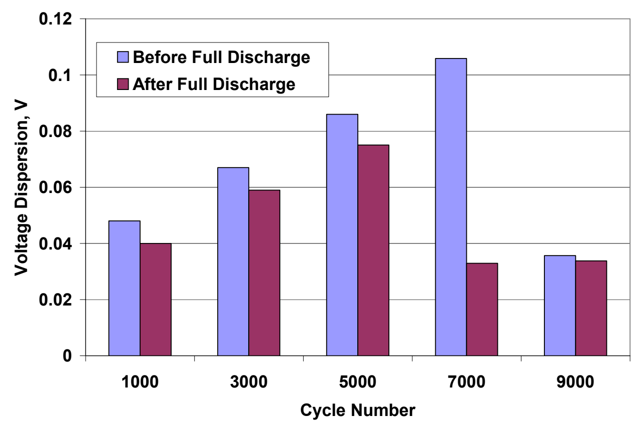
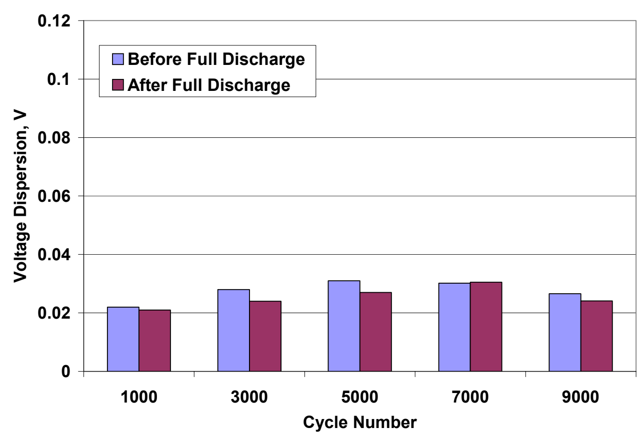


Figure 9.—End-of-Discharge Voltage during LEO cycling.



(a)



(b)

Figure 10.—Effect of characterization procedures on cell (a) EOCV dispersion; and (b) EODV dispersion.

C. Full Capacity After LEO Cycling

At 1000 cycle intervals, the battery is fully discharged to 24 V at the LEO rate to measure the full capacity in the battery during LEO cycling. As seen in figure 11, we observe that the battery delivers fewer Ah as the number of cycles increases. Since the charge voltage cut-off limit is controlled on the battery-level (the sum of the series cell voltages), certain cells do not reach their full voltage during the charge period. On discharge, these same cells will determine the capacity delivered by the battery. The cell voltage dispersion tends to get larger over several thousands of cycles, so the battery delivers less and less capacity with the increase in cell voltage dispersion. When the cells are brought closer together by cell balancing, the battery can deliver more capacity under the same test conditions. At 9000 cycles, the 21.4 Ah delivered after LEO cycling is identical to that delivered at 6000 cycles.

A lengthy taper charge period can also result in bringing cell voltages closer together, so more capacity is delivered from a 100 percent DOD discharge than from a full discharge after LEO cycling. For example, at 4000 cycles, the 100 percent DOD capacity delivered was 24.5 Ah (see table 4) whereas 21.9 Ah was delivered from the full discharge after 4000 LEO cycles (see fig. 11), a 2.6 Ah difference. Similar results are observed when comparing the capacity delivered at 6000 and 9000 cycles.

D. Specific Energy

Specific energy for the battery is calculated using the mass of the entire flight battery assembly, including cell stack, battery wiring, deck plate, and connectors. In aerospace-design batteries, mass packaging factors can vary widely depending upon the requirements and constraints of individual missions, even for batteries of the same chemistry. As a result, battery-level specific energy can also vary significantly. In order to meet mission requirements, the lander battery was fortified with robust construction designed to tolerate the impact it would sustain during its landing on the surface of Mars. The specific energy values are indicative of this sturdy construction. The specific energy averages 76 watt-hours per kilogram (Wh/kg) at 100 percent DOD and 32 Wh/kg during LEO cycling.

X. Cell Level Performance

During LEO cycling, Cells 6 and 7 consistently have the lowest EODVs. The cells are near the top of the stack and have temperatures in the middle range of the temperature distribution. The cycle performance shown in figure 4 shows Cells 6 and 7 diverging from the rest of the battery. At ~cycle 7000, these cells are only at ~3.95 V when the high rate charge is terminated based on the battery cutoff of 32.0 V, while the other cells in the battery all have voltages above 4.0 V. The lower EOCV indicates that these cells are at a lower SOC than the rest of the battery. This is consistent with the EODV behavior as well, where Cells 6 and 7 are approximately 20 mV lower that the other cells in the battery.

Figure 12 shows the OCV recovery for each cell after a full discharge at the LEO discharge rate following the LEO charge at cycle 6000, and the OCV recovery following the 100 percent DOD capacity check that followed. In both cases, Cells 6 and 7 have the lowest EODV.

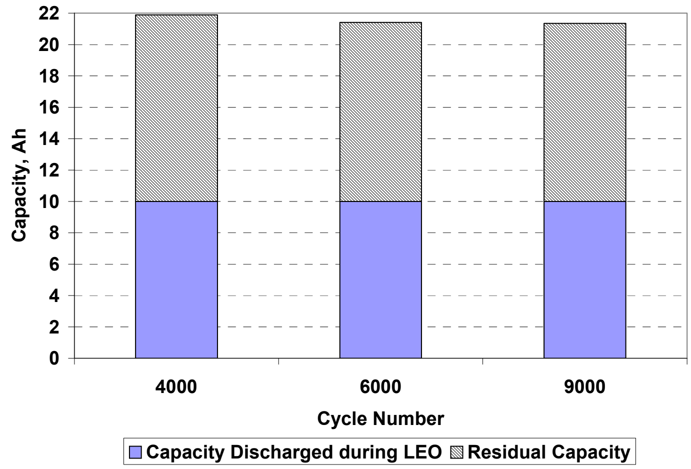
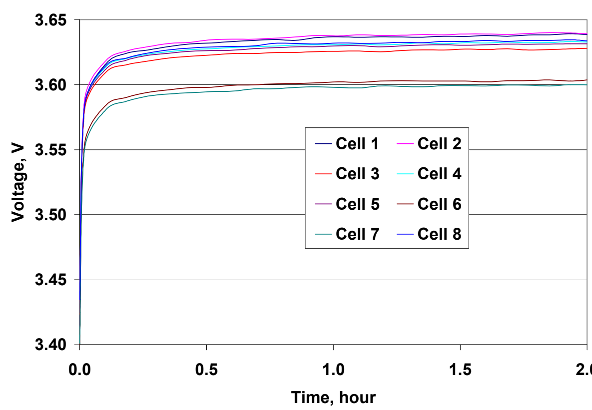
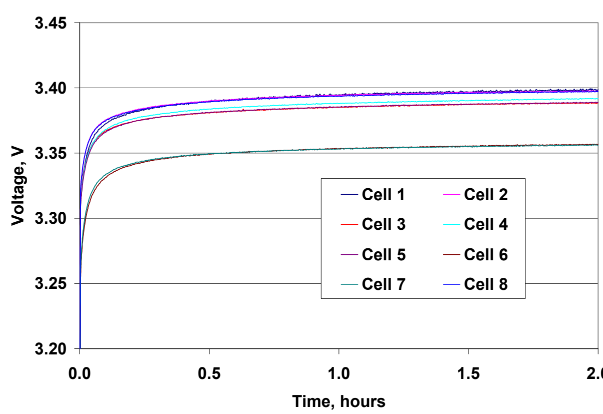


Figure 11.—Capacity remaining in battery after LEO discharge.



(a)



(b)

Figure 12.—OCV recovery versus time at 6000 cycles for 2 hours after full discharge at LEO rate: (a) after LEO cycling; and (b) after 100 percent DOD capacity check.

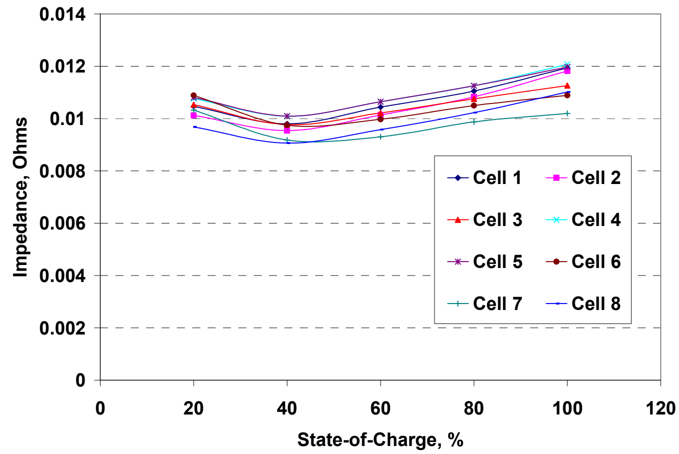


Figure 13.—Cell impedances at 6000 cycles at different SOCs.

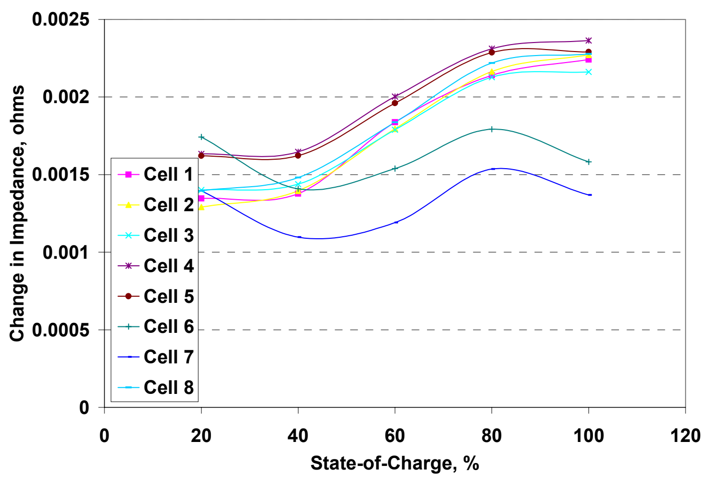


Figure 14.—Change in cell impedances from pre-LEO characterization to 6000 cycles.

Cell impedance as a function of state of charge for cycle 6000 is shown in figure 13. Cell 7 has the lowest impedance at the highest states of charge. The impedance of Cell 6 is generally in the middle range at most states of charge. Figure 14 shows the change in impedance between the pre LEO-cycling measurement and the measurement at 6000 cycles as a function of SOC.

In future work, additional analysis will be performed to further understand the relationships between the individual cell operating voltages, the cell impedances, the thermal characteristics of each cell relative to the other cells in the stack, and the battery level interactions.

XI. Conclusion

The 2001 Mars Surveyor Program Lander battery has achieved over 9000 LEO cycles at 40 percent DOD. The battery is performing well and continues to deliver required capacity at 0 °C during the LEO testing. If the current performance trends continue, it is projected that the battery can attain thousands of additional LEO cycles before it fails. The eight cells are operating uniformly together and it has been demonstrated that several thousand cycles can be achieved before cell voltage dispersion reaches 100 mV on charge. By periodically rebalancing the cells, battery life can be extended and can possibly extend the life of the mission. Future analysis will focus on identifying the causes of cell imbalance and methods for prolonging battery life.

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13. ABSTRACT ***(Maximum 200 words)***

A flight-qualified, lithium-ion (Li-ion) battery fabricated for the Mars Surveyor Program 2001 lander is undergoing life-testing at low temperature under a low-Earth-orbit (LEO) profile to assess its capability to provide long term energy storage for aerospace missions. Li-ion batteries are excellent candidates to provide power and energy storage for satellites in LEO due to their high specific energy, high energy density, and excellent low temperature performance. Although Li-ion batteries are increasingly being used for aerospace missions in geosynchronous orbit, some challenges still remain before they can be deemed a suitable replacement for their secondary alkaline battery counterparts in long cycle life LEO applications. Life cycle testing of this battery is being conducted in the laboratory to characterize battery-level performance and to examine the dynamics of individual cells within the stack under aerospace conditions. Data generated in this work is critical to establish confidence in the technology for its widespread use in manned and unmanned missions. This paper discusses the performance of the 28 volt, 25 ampere-hour battery through 9000 LEO cycles, which corresponds to over 18 months on LEO orbit. Testing is conducted at 0 °C and 40 percent depth-of-discharge. Individual cell behaviors and their effect on the performance of the battery are described. Capacity, impedance, energy efficiency, end-of-discharge voltages, and cell voltage dispersions are reported. Relationships between cell temperatures, cell impedance, and their relative position in the battery stack are discussed.

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